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Epithermal Neutron Source for Neutron Resonance Spectroscopy (NRS) using High Intensity, Short Pulse Lasers

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A neutron source for neutron resonance spectroscopy (NRS) has been developed using high intensity, short pulse lasers. This measurement technique will allow for robust measurements of interior ion temperature of laser-shocked materials and provide insight into equation of state (EOS) measurements. The neutron generation technique uses protons accelerated by lasers off of Cu foils to create neutrons in LiF, through (p,n) reactions with ^{7}Li and ^{19}F. The distribution of the incident proton beam has been diagnosed using radiochromic film (RCF). This distribution is used as the input for a (p,n) neturon prediction code which is compared to experimentally measured neutron yields. From this calculation, a total fluence of 1.8×10^{9} neutrons is infered, which is shown to be a reasonable amount for NRS temperature measurement.

A concrete understanding of material equation of state (EOS) is of underlying importance in many fields (e.g. planetary physics, geophysics, shocked matter physics, warm-dense matter physics). One of the most fundamental quantities in EOS measurement is temperature. A major hurdle to temperature measurements is that conventional optical diagnostic techniques cannot be used to probe the interior of opaque materials, such as metals. A new technique known as neutron resonance spectroscopy (NRS)[1,2] avoids this problem by using neutrons to diagnose temperature.

In NRS, a beam of neutrons, of 1-100eV, is sent through a sample made of or doped with a material possessing strong neutron absorption resonances at these energies (e.g. W, Mo). When passing through the material neutrons are absorbed by nuclear resonances in the ions, which can be seen as negative-peaks in the resulting neutron spectrum. From these peaks, the spectral broadening and shifting can be measured, enabling determination of ion temperature and velocity, respectively.

So far, NRS experiments have been performed using spallation neutrons from proton accelerator rings. In order to provide shocked states for EOS investigation at these facilities, detonation of chemical explosives accelerate flyer plates into the material of interest. This technique is difficult to employ and has a prohibitively high cost. On the other hand, nanosecond lasers have been used extensively to study shocked[3] and warm-dense matter[4]. Many of these laser facilities are equipped with high intensity, short pulse lasers that can be used concurrently with the nanosecond laser pluse.

The use of high power, high intensity laser beams to accelerate protons has been well studied[5–7]. These protons can be converted into epithermal neutrons using a material with a high cross-section for (p,n) reactions (e.g. LiF)[8] and then moderated down to appropriate energies for NRS. The picosecond scale pulse length of the laser (as with the accelerator beam) and the ability to dope only a given section of the material, enabling temporal and spatial effects (e.g. rarefaction) to be neglected.

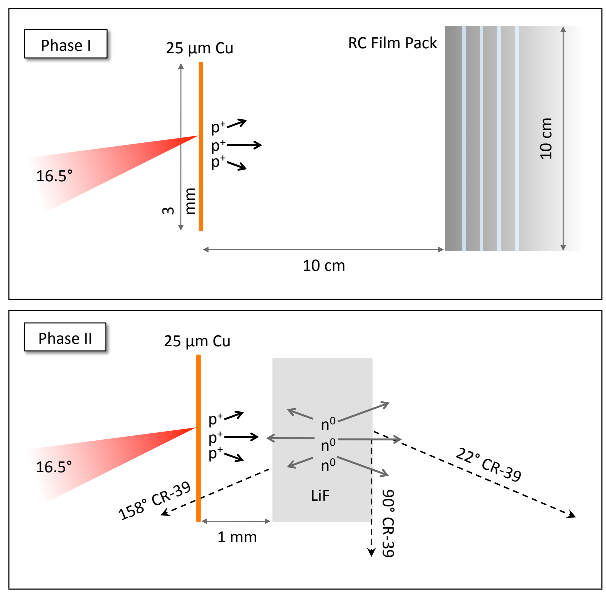

FIG. 1: Experimental layout showing Phase I, measurement of proton distribution using RCF and Phase II showing neutron production through ^{7}Li(p,n)^{7}Be reactions and neutron measurement using CR-39.

In this letter, it is shown that neutrons produced through (p,n) reactions with laser accelerated protons are a route to performing NRS measurements in laser shocked materials.

The experiment was performed on the Titan Laser of the Jupiter Laser Facility at the Lawrence Livermore National Laboratory. The Titan laser is a Nd:glass laser with λ_{laser} =1054 nm, used at best focus (spot diameter of 7 μm, with 20% of energy) and shortest pulse length, 0.7 ps. The laser was focused on Cu foil of 25 μm thickness, which accelerated high energy electrons in the forward direction setting up an electric field that accelerated a quasi-neutral proton beam from a hydrocarbon debris layer on the rear of the target. In Phase I, these protons were then incident on a radiochromic film (RCF) stack (see Phase I of Fig.1) to measure the proton distribution or, in Phase II, they were incident on a 0.9 mm LiF converter foil (see Phase II of Fig.1). The LiF converter foil contains large cross-sections for (p,n) reactions (see Fig. 3) which generated neutrons that were detected on absolutely calibrated CR-39 detectors at 3 different angles.

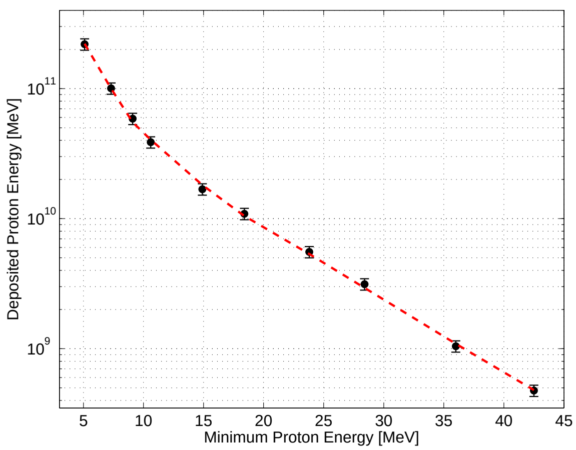

FIG. 2: RCF data from a shot with 140 J on target and laser intensity of $1{\times}10^{20}$ W/cm^2. Each data point represents one layer of RCF, where the horizontal axis shows the minimum proton energy neccesary to reach that layer. The experimental data is shown with circles (•). The dashed line is the best fit of a two temperature maxwellian as described in the text.

In Phase I, radiochromic film (RCF) stacks were used to characterize the proton beam distribution. RCF is an absolutely calibrated film[9] which contains an organic dye that increases in opacity with exposure to ionizing radiation. The RCF stack consists of alternating layers of Al filters and RCF. A total of ten sheets of RCF were used to give an energy resolution from 5.1 to 42.5 MeV. The lower limit was chosen to avoid signal contamination from other high energy ions accelerated off the foil. Note that the lower limit does not add significant error to our neutron predictions as the probability of neutron production at lower energies is quite small (see Figure 4). The stopping of the protons and the energy that they deposited in each layer of film was calculated with the collisional monte-carlo code SRIM[10].

In order to fit the data, a two temperature maxwellian proton distribution was assumed, $\frac{dN}{d\mathcal{E}} = \frac{N_1}{\sqrt{\pi \mathcal{E} T_1}} e^{-\mathcal{E}/T_1} + \frac{N_2}{\sqrt{\pi \mathcal{E} T_2}} e^{-\mathcal{E}/T_2}$, which is a function of proton energy, $\mathcal{E}$. The parameters N_1, N_2, T_1 and T_2 representing proton number and proton temperature, respectively, were optimized to minimize the reduced χ^2 fit to the data. The result of this fit is compared with experimental data, shown in Figure 2. The best fit is given by T_1=2.9 MeV, $N_1 = 4.34 \times 10^{13}$, T_2=10.27 MeV and $N_2 = 5.44 \times 10^{12}$, with a reduced χ^2 of 0.41. The conversion efficiency into protons above 5.1 MeV is 3.5% with is consistent with previous results[7]. The largest error in the RCF comes from the batch to batch error which is 10%[9].

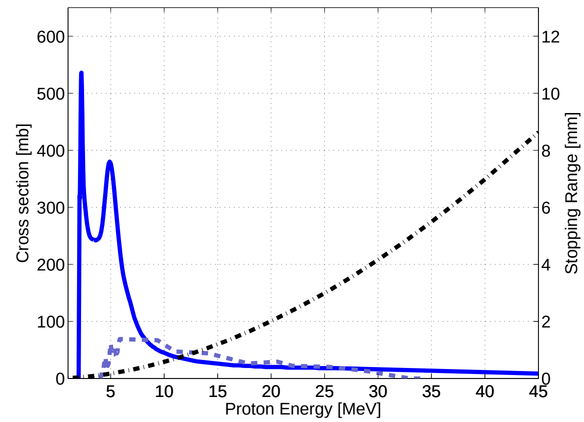

FIG. 3: Plotted on the left axis, are cross sections for ^{7}Li(p,n)^{7}Be (solid line) and ^{19}F(p,n)^{19}Ne (dashed line) vs incident proton energy. The other stable isotope of Li, is ^{6}Li which has no documented (p,n) cross-sections. On the right axis is the mean stopping range of protons in LiF as calculated with SRIM (dash-dotted line).

In the Phase II, a LiF block of 0.9 mm was placed about 1 mm in back of rear of the Cu foil so that the proton beam was incident on the LiF converter. RCF was not used concurrently, as the proton beam was absorbed the the LiF converter. In order to record the neutron emission, three stacks of absolutely calibrated CR-39 detectors were placed at 22, 90 and 158 degrees from rear target normal. CR-39 is a plastic that can be damaged indirectly by neutrons through knock-on protons and has been used previously in laser generated proton experiments[8]. To determine the sensitivity of CR-39 to neutrons, the cross section from a ^{252}Cf source was used. This is a good assumption given that the CR-39 sensitivity is nearly constant with neutrons 0.5 to 5 MeV[11]. The error in this measurement is calculated by adding in quadrature the variation in the background of unexposed CR-39 and the variation within the CR-39 detector stack.

The code DOWNSPEC[12] was used to calculate the production of neutrons created in a given (p,n) converter material by given energy protons. The code simultaneously calculated the stopping of incident protons as well as calculating their cross-sections for (p,n) type reactions (see Fig. 3). This allows for determination of angular and energy resolved neutron yields. The code uses the continuous deceleration approximation (CDA) so it does not account for scattering or for energy broadening for a single energy incident proton.

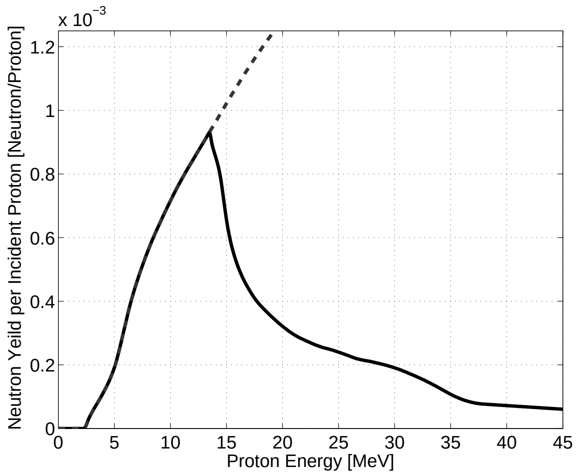

FIG. 4: Angularly integrated neutron production probability (NPP) of protons of a given energy in LiF. The solid line is for 0.9 mm thickness, as used in the experiment, and the dotted line is for an infinite block of LiF.

A useful way to evaluate a material's ability to produce (p,n) neutrons is to look at neutrons produced per incident proton (NPP) at a given energy, as shown in Figure 4. The NPP is more useful than the cross section alone, because it also takes into account the stopping of protons in the material.

To predict the number of neutrons produced, the proton distributions (see Figure 2) were used as inputs in DOWNSPEC, which gave angularly resolved neutron yields. These predicted yields are plotted in Figure 5 against the experimentally measured CR-39 yields of shots. It is worth noting that there is shot-to-shot variation for shots with the same laser energy. This fluxuation is common in short pulse laser experiments[6,7].

In this letter, the capacity to predict and generate beams of $1.8{\times}10^9$ neutrons within a few picoseconds has been demonstrated. Using statistical error analysis, the predicted fractional uncertainty in tempetature, T, is $\Delta T = 2/\sqrt{N}$. Where N is the number of neutrons that are useable for NRS measurements (i.e. they pass through the target and are in the 1-100 eV range), $\sqrt{N}$ is the statistical noise and 2 is the degrees of freedom. Thus for temperature measurement with 1% accuracy 4×10^4 useable neutrons are required. The moderator setup must therefore capture the epithermal neutrons, direct them towards the shocked target and downshift their energy with an efficiency of $> 2.2 \times 10^{-5}$. While in-depth modeling is necessary to determine and optimize the moderator setup, this efficiency seems achievable.

To conclude, the viability of short-pulse laser produced epithermal neutrons as viable path for an NRS temperature diagnostic has shown. Future experiments on the Titan laser are underway that will illustrate the capacity to moderate and collimate neutrons for NRS and to ultimately perform NRS temperature measurements on a sample ablatively loaded with a nanosecond laser pulse.

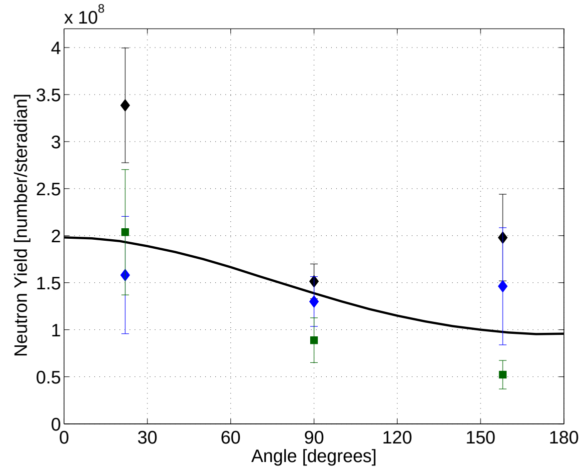

FIG. 5: Experimental neutron yields (CR-39) plotted against predicted. Two shots of 127 J plotted with diamonds (♦,♦) and one shot of 114 J is shown with squares (■). The predicted yield, using a 140 J shot, is shown as the solid line.

Acknowledgments

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[1] V. W. Yuan, J. D. Bowman, D. J. Funk, G. L. Morgan, R. L. Rabie, C. E. Ragan, J. P. Quintana, and H. L. Stacy, Phys. Rev. Lett. **94**, 125504 (2005).

[2] D. C. Swift, A. Seifter, D. Holtkamp, V. Yuan, D. Bowman, and D. A. Clark, Phys. Rev. B **77**, 092102 (2008).

[3] R. F. Smith, J. H. Eggert, A. Jankowski, P. M. Celliers, M. J. Edwards, Y. M. Gupta, J. R. Asay, and G. W. Collins, Phys. Rev. Lett. **98**, 065701 (2007).

[4] R. P. Drake, *High-Energy-Density Physics: Fundamentals, Inertial Fusion, and Experimental Astrophysics* (Springer, 2006).

[5] A. J. Mackinnon, Y. Sentoku, P. K. Patel, D. W. Price, S. Hatchet, M. H. Key, C. Anderson, R. Snavely, and R. R. Freeman, Phys. Rev. Lett. **99**, 215006 (2002).

[6] J. Fuchs, P. Antici, E. D'Humières, E. Lefebvre, M. Borghesi, E. Brambrink, C. A. Cecchetti, M. Kaluza, V. Malka, M. Manclossi, et al., Nature Phys. **2**, 48 (2005).

[7] L. Robson, P. T. Simpson, R. J. Clarke, K. W. D. Ledingham, F. Lindau, O. Lundh, T. Mccanny, P. Mora, D. Neely, C. G. Wahlström, et al., Nature Phys. **3**, 58 (2007).

[8] K. L. Lancaster, S. Karsch, H. Habara, F. N. Beg, E. L. Clark, R. Freeman, M. H. Key, J. A. King, R. Kodama,

K. Krushelnick, et al., Phys. Plasmas **11**, 3404 (2004).
[9] D. S. Hey, M. H. Key, A. J. Mackinnon, A. G. MacPhee, P. K. Patel, R. R. Freeman, L. D. V. Woerkom, and C. M. Castaneda, Rev. Sci. Instrum. **79**, 053501 (2008).
[10] J. F. Ziegler, J. P. Biersack, and M. Ziegler, *SRIM-The stopping and range of ions in matter* (Lulu.com, 2008).
[11] D. E. Hankins, S. G. Homann, and B. Buddemeier, Lawrence Livermore National Laboratory Report, UCRL-53833 (1989).
[12] D. C. Swift, J. M. McNaney, D. P. Higginson, and F. N. Beg, Lawrence Livermore National Laboratory Report, LLNL-TR-417474 (2009).